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Relativistic electron beam interaction and K_α - generation in solid targets

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ABSTRACT

When fs laser pulses interact with solid surfaces at intensities $I\lambda^2 > 10^{18}$ W/cm^2 μm^2, collimated relativistic electron beams are generated. These electrons can be used for producing intense X-radiation (bremsstrahlung or K_α) for pumping an innershell X-ray laser. The basic concept of such a laser involves the propagation of the electron beam in a material which converts electron energy into appropriate pump photons.

Using the ATLAS titanium-sapphire laser at Max-Planck-Institut für Quantenoptik, we investigate the generation of hot electrons and of characteristic radiation in copper. The laser (200 mJ/130 fs) is focused by means of an off-axis parabola to a diameter of about 10 μm. By varying the position of the focus, we measure the copper K_α - yield as a function of intensity in a range from 10^{15} to 2×10^{18} W/cm^2 while keeping the laser pulse energy constant. Surprisingly, the highest emission is obtained at an intensity of about 10^{17} W/cm^2 . However, this result is readily explained by the weak scaling of the hot-electron temperature with intensity. An efficiency of 2×10^{-4} for the conversion of laser energy into copper K_α is measured.

Simulations of the interaction of the hot electrons with the cold target material and the conversion into X-rays are carried out by means of the TIGER/ITS code, a time-independent, coupled electron/photon Monte Carlo transport code. The code calculates the propagation of individual electrons and the generation of photons in cold material. Comparison of the code predictions with our data shows an efficiency of 15% for the generation of electrons with energies in the 100 keV range.

A second experiment involves the demonstration of photopumping of an innershell transition in cobalt by the copper radiation. Comparing the emission with the one of nickel, which is not photopumped by copper K_α photons, an enhancement of more than a factor of two was obtained. An essential part of this experiment is the use of a 1 mm carbon sheet to block the electrons from the material to be photopumped.

Keywords: X-ray lasers, laser plasmas, characteristic X-rays

1. INTRODUCTION

Significant progress in the field of soft X-ray lasers has been achieved with the observation of saturated emission at wavelengths below 10 nm and with a considerable reduction of the required pump laser energies (see, for example, the papers in [1]). Unfortunately, however, the problem of generating gain in the keV region is still unsolved. It is in this region, that a number of exciting applications of coherent X-rays, such as holography, time resolved diffraction or lithography are waiting to be exploited.

The main obstacle to realizating a hard X-ray laser is, of course, the extremely high intensity required to pump it. Simple scaling laws[2] derived from the Einstein relations lead to intensities around 10^{20} W/cm^2 for a laser at 1 keV. Fortunately, in recent years, considerable progress in the development of ultrashort-pulse lasers[3-5] in particular the invention of the CPA technique[6] has made it possible to generate intensities even exceeding this value. Thus, it seems feasible to reconsider keV X-ray lasers taking into account the new generation of ultrashort-pulse lasers.

It has been known for some time that at intensities of about 10^{18} W/cm^2 (at wavelengths around 1 μm) a new quality of interaction of laser pulses with a plasma is induced, owing to the fact that the electrons quivering in the laser field become relativistic. These relativistic effects include self-focusing of the laser pulse, subsequent generation of channels of propagation and generation of directed electron beams.[6-12] We recently pointed out that a combination of these effects can be used to alleviate considerably the problem of pumping a keV X-ray laser.[13] The favorable features considered include an increase in the applied intensities due to self-focusing, formation of a relatively long channel in which the energy is deposited and application of the relativistic electrons for traveling-wave excitation with the velocity of light.

In the present paper we first discuss the concept of a relativistically supported X-ray laser, and present simulations to lay down the pumping requirements. In the second part of the paper we report experiments which investigate basic features of hot electron generation and propagation in cold material.

2. CONCEPT OF A RELATIVISTIC PLASMA-PUMPED X-RAY LASER

At intensities $I\lambda^2 \approx 10^{18}$ W μm^2 /cm^2 the velocity of the electrons oscillating in the laser field becomes so high that a significant mass increase takes place. The resulting reduction in the time-averaged plasma frequency leads to an increase of the plasma refractive index for the laser pulse. Thus, for a laser pulse with an intensity maximum on axis a self-focusing mechanism takes place which overcomes the beam spread due to diffraction at a critical power given by[14]

$$P_c = 17\, N_c/N_e \text{ [GW]}, \qquad (1)$$

where N_c and N_e are the critical electron density and the plasma electron density respectively. PIC simulations show that relativistic self-focusing leads to a pulse propagation channel only a few wavelengths wide with a length of many diffraction distances.

A second relativistic effect consists in acceleration of electrons due to the Lorentz force, as given by $v_{osc} \times B_L$, where v_{osc} is the quiver velocity of the electrons in the laser field and B_L is the magnetic field of the electromagnetic wave. It is well known that for a plane wave the Lorentz force will not eventually lead to forward acceleration of the electrons, since all of the energy will be returned to the field after the laser pulse.[15] PIC simulations show, however, that under realistic conditions, i.e. for a laser pulse with an intensity profile peaking on axis, or in a plasma, a number of mechanisms lead to net acceleration of the electrons. Collimated electron beams with a Boltzmann distribution with energies of several MeV are predicted.[9-12]

Reviewing X-ray laser schemes which might operate under the conditions outlined above, one has to conclude that the ones most successful in the soft X-ray region, viz. recombination pumping and electron collisional excitation, are very difficult to implement with a relativistic plasma. The high electron temperatures and the corresponding low cross-sections for atomic interactions preclude the generation of a high pumping rate. Innershell photopumping, however, seems to be well suited to application of relativistic effects.

While the principles of this scheme were already laid down many years ago,[16] its realization has so far been impeded by major difficulties. Consider the particular case of lasing on a K_α - transition as a representative example of innershell excitation:

1. Inversion on an innershell transition is generated only by appropriate photons, i.e. photons above the K-edge of a material. Electrons invariably destroy the inversion due to their large cross-section for generating L-shell holes. Thus, the electrons generated by the photoionization and Auger processes themselves and those subsequently produced by collisional ionization terminate the gain and eventually lead to absorption.
2. Rapid nonradiative decay of the K-holes (Auger decay) results in a high loss rate of the generated inversion.
3. The high background absorption of the lasing material (invariably resulting from photoionization from the L-shell and higher shells) requires a high gain coefficient to get into the net gain region.

Fortunately, as will be shown below, the first two obstacles can be overcome by reducing the pump pulse duration to values within reach of present short-pulse lasers. The third problem leads to a threshold pump power which has to be exceeded to achieve net gain.

Computer simulations were carried out with RELAX, an atomic kinetic code which calculates K- and L-hole populations, taking into account the electron avalanche generated by collisional ionization from outer shells. As a first example, in fig. 1 the result for an argon K_α - laser at 2.96 keV is shown. Potassium K_α - photons ($h\nu$ = 3.3 keV) are taken to be the pump. The argon K-edge is at 3.21 keV. The pump photons are assumed to be emitted from the side of a thin cylinder which is surrounded by the argon gain medium at a density of 10^{21} cm^{-3}.

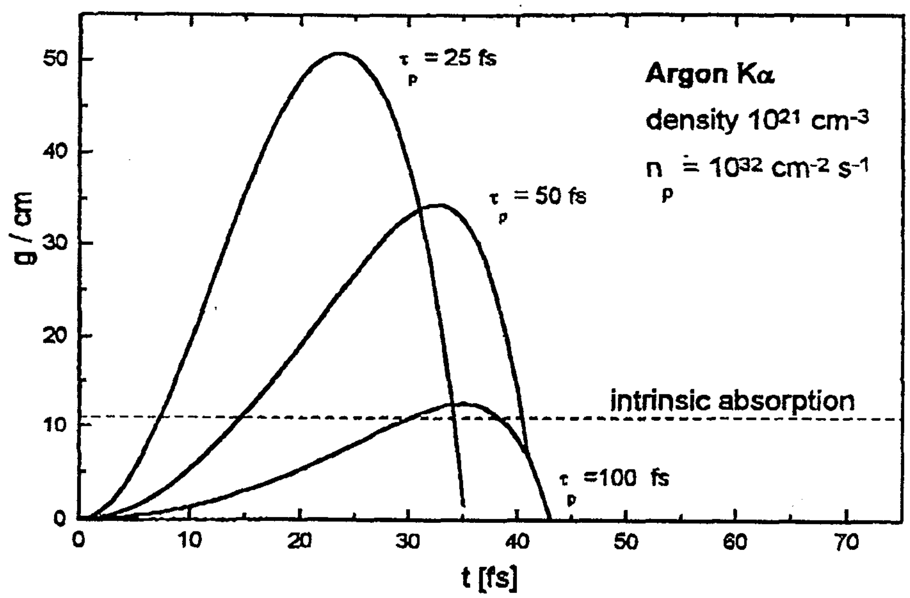

Fig. 1: Time evolution of the $K_{\alpha 1}$ gain coefficient in argon for pump pulse durations of 25, 50 and 100 fs. Potassium K_α - radiation is assumed for the pump. For a radiating cylinder of 10 μm diameter and 1mm length the indicated pump photon flux of 10^{32} photons/cm^2 s corresponds to a total number of 8 x 10^{14} pump photons for a 25 fs pump pulse. The curves demonstrate the increase in the gain coefficient when the pump pulse is shortened.

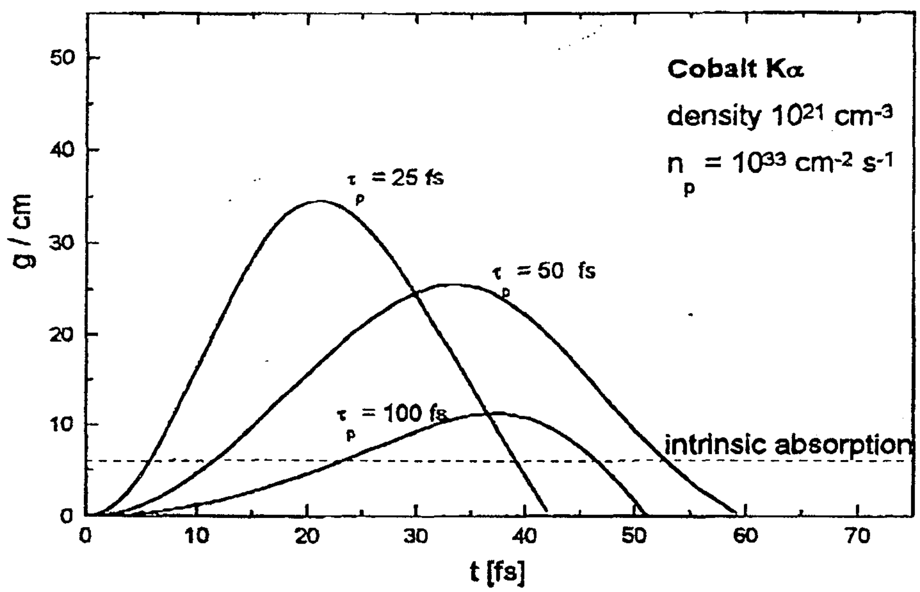

Fig. 2: Temporal evolution of the $K_{\alpha 1}$ gain coefficient in cobalt for pump pulse durations of 25, 50 and 100 fs. Copper K_α - radiation is assumed for the pump. The indicated pump photon flux of 10^{33} photons/cm^2 s corresponds to a total number of 8 x 10^{15} pump photons for a 25 fs pump pulse, if a radiating cylinder with a diameter of 10 μm and 1 mm length is assumed.

As a second example we show the temporal gain evolution for cobalt as a gain medium (Fig. 2). The energy of the $K_{\alpha 1}$ - photons is 6.93 keV. The simulations assume copper K_α - pump photons with an energy of 8.04 keV, above the cobalt K-edge at 7.7 keV. Fig. 2 shows the gain history at a cobalt density of 10^{21} /cm^3 .Note that the pump photon flux was raised by a factor of 10 as compared to argon in order to get a similar gain coefficient. The pump photon flux of 10^{33} /cm^2 s easily drives the system into the net gain region.

The good news from these simulations is that in both cases significant net gain is achieved and that a measurable gain-length is obtained for a gain medium of 1 mm in length. However, meeting the above pumping requirements is certainly not a trivial task. Pump energy could be saved by further shortening the pump pulse, however, the shorter the pump pulse the higher must be the energy of the electrons in order to avoid a mismatch between the electron velocity and the velocity of light. A further problem arises from the requirement that only a small fraction of the electrons are allowed to reach the gain medium, since as mentioned above, they generate L-holes, the lower level of the lasing transition. A high degree of collimation of the electron beam is therefore essential for the scheme to be feasible.

3. EXPERIMENTS

Experiments were carried out in our laboratory in order to investigate the mechanisms of electron beam and characteristic X-ray generation and demonstrate the basic feasibility of photopumping. The ATLAS titanium-sapphire laser at MPQ, used for these investigations, has a power of 2 TW with a pulse duration of 130 fs. The laser pulse was focused p-polarized on copper targets using an off-axis parabola. The peak intensity reached at best focus was 2×10^{18} W/cm^2. An X-ray CCD in the energy readout mode[17] was used for detection. The CCD was absolutely calibrated by means of a radioactive Mn^{55} source.

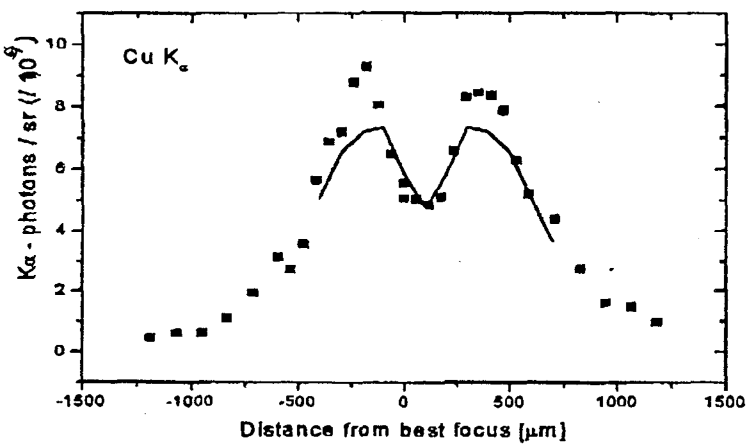

Fig. 3: Copper K_α - photons per sterad emitted from the front of a slab target. Negative values of the abscissa indicate a focus in front of the target. For positive values the focus is within the target. Squares: experimental data. Solid line: simulation result using the TIGER/ITS code. For details see text.

Applying no prepulse (except for the intrinsic one, see[18]) it was found that the spectrum in the hard X-ray region consisted predominantly of K_α - photons (hv = 8.03 keV). The K_α - yield was measured in an intensity range extending several orders of magnitude. The intensity was varied by defocusing the laser beam, thus the energy on target was kept constant. In this way the copper K_α - yield shown in fig. 3 was measured.

The most interesting aspect of these data is that the maximum number of photons is not obtained at best focus but with a considerably defocused beam. This observation can be explained by realizing that - according to theory - the electron temperature depends only weakly on the applied intensity[19] a fact which is also predicted by PIC simulations.[20,21] Moreover, for the front side emission the X-ray yield of colder electrons is higher since the electrons do not penetrate deep into the target. The solid line in fig. 3 is a theoretical result obtained with the TIGER/ITS Monte-Carlo electron/photon propagation code, (originally called ETRAN[22]), scaling the electron temperature as

$$kT_e \sim (I\lambda^2)^{1/3} \tag{2}$$

and taking the intensity distribution of the focused pulse into account. For this simulation the electron temperature at the highest intensity in the center of the focal spot was assumed to be 100 keV. Details of this experiment and the simulations will be published elsewhere.[23]

A significant feature of these measurements, which is not understood at the moment, is the slight asymmetry of the data around the position of best focus. To account for this asymmetry, the theoretical curve had to be shifted by 100 μm in the direction of propagation of the laser beam. Thus, it seens that a focus located within the target generates hotter electrons than a focus exactly at the target surface.

The maximum photon yield of about 10^{10} copper K_α - photons per steradian corresponds to an efficiency of 2 x 10^{-4} for conversion of laser energy into these photons. By matching the simulations to the measured absolute photon number we arrive at a total number of 1.2 x 10^{13} electrons with energies between 10 and 100 keV at best focus. The absolute number of electrons increases if the beam is defocused. The conversion efficiency into hot electrons, assumed to be constant in the theory, becomes 15%, which is in a similar range as measured by other laboratories.[24,25]

An experiment was carried out to demonstrate the possibility of using the strong copper K_α - radiation to photopump cobalt K_α - emission. Targets were fabricated which consisted of a 10 μm copper foil backed by 1 mm of carbon and terminated with a final layer of 15 μm of cobalt or 10 μm of nickel. The copper K_α - photon energy is above the cobalt K-edge but below the one of nickel. A significantly higher yield of cobalt K_α - radiation is therefore a signature for photopumping. The carbon layer was inserted to act as an electron blocker, preventing K-holes from being generated in either material by the electrons. Electrons with an energy of up to 500 keV are stopped by 1 mm of carbon.[26]

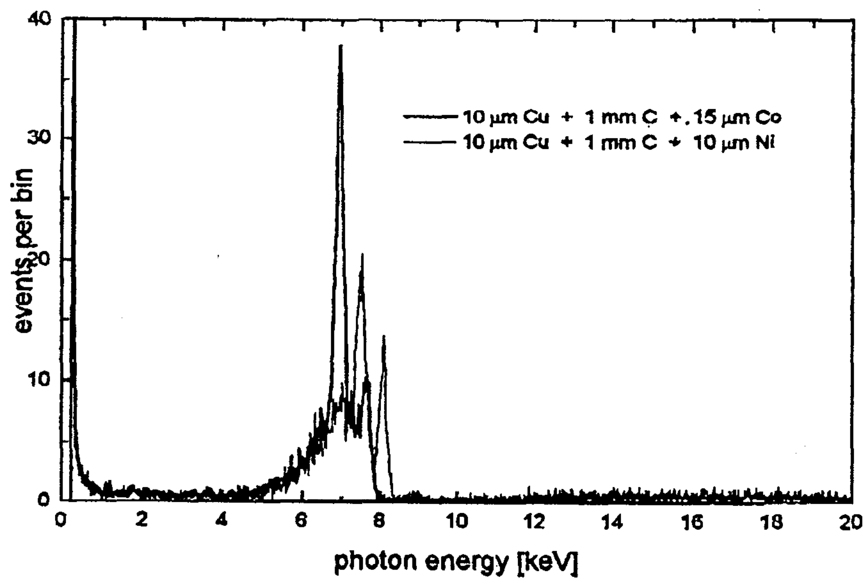

Fig. 3: Result of an experiment to demonstrate photopumping of cobalt K_α by characteristic radiation of copper. Spectra from two types of targets are shown which have either a cobalt or nickel backing. The cobalt K_α – line at 6.9 keV is observed to exceed the corresponding nickel line at 7.3 keV by more than a factor of two. The copper pump line at 8.04 keV is seen in the case of nickel, but not for cobalt, for which material it is above the K-edge.

The results are shown in fig. 3, which displays the hard X-ray spectra obtained by observing from behind the target. The radiation was filtered by 100 μm of beryllium and 15 μm of cobalt. It is seen that the cobalt K_α - emission is more than a factor of two higher than the one of nickel. This enhancement demonstrates, at least in principle, the feasibility of an efficient generation of K-holes by photopumping and also shows that the idea of stopping the electrons before they reach the gain medium is a reasonable one. An improved version of the experiment, optimized by carefully choosing the thicknesses of the various layers and the composition of the blocking layer is planned for the near future.

5. CONCLUSIONS

The intensities required to pump an X-ray laser in the 10 keV region considerably exceed 10^{18} W/cm^2. At such intensities relativistic effects such as self-focusing, channeling and generation of directed electron beams occur. A scheme has been presented which uses these effects to improve the conditions for pumping an innershell X-ray laser. Favorable features include a saving in pump power due to self-focusing and the possibility of traveling-wave excitation due to the relativistic propagation of the electron beam. Nevertheless, the pumping requirements for a keV X-ray laser are still extremely high. As an example, simulations predict that close to 10^{15} pump photons, emitted in less than 100 fs are necessary for driving an argon K_α - laser into the region of measurable gain. Furthermore, a high degree of collimation of the electrons is essential in order to prevent them from reaching the gain medium and to generating an absorption.

Experiments show that intense characteristic copper radiation is readily obtained upon interaction of a fs laser pulse with a solid copper target. We measured the number of copper K_α - photons emitted from the front side of a copper slab target using a weakly relativistic intensity of 2 x 10^{18} W/cm^2 to be 10^{10}. Comparison of this number with the result of a simulation yields a conversion efficiency of 15% into suprathermal electrons.

As a first step towards an X-ray laser in the keV region, photopumping of cobalt K_α - radiation at 6.9 keV by copper L-shell radiation was demonstrated. A gain demonstration, however, requires considerably higher pump power and the application of shorter pump pulses.

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